220706

UCRL-JC-111507
PREPRINT

Development of Laser-Driven Heat Exchanger Rocket for Ground-to-Orbit Launch

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This paper was prepared for submittal to
The 43rd Congress of the Institute of Aeronautics and Astronautics
370 L' Effant Promenade
S. W. Washington, DC 20024
August 28 through September 4, 1992

August 1993

DEVELOPMENT OF LASER-DRIVEN HEAT
EXCHANGER ROCKET FOR GROUND-TO-ORBIT

DISCLAIMER

DEVELOPMENT OF LASER-DRIVEN HEAT EXCHANGER ROCKET FOR GROUND-TO-ORBIT LAUNCH

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A novel heat-exchanger technology is presented which efficiently couples laser energy to hydrogen gas at fluxes of up to 1000 W/cm^2 and specific power levels of 1000 W per gram of heat exchanger. The planar heat exchanger uses laminar flow in submillimeter-scale channels to achieve maximum heat transfer with minimum pressure drop. Low cost techniques have been developed for fabricating multimegawatt heat exchangers with output temperatures greater than 1000 C. This heat exchanger technology makes possible a class of laser-driven rocket vehicles with 600 to 800 second specific impulse. The vehicle performance is sufficient to launch payloads in excess of 1 kg per megawatt of laser power into low Earth orbit.

Sample heat exchangers have been fabricated, and experiments are planned. Because the heat exchanger rocket is omnivorous (i.e., will operate with any type of laser or radiant energy source) significant demonstrations of laser-driven vehicles may be possible in the near future.

Introduction

The concept of laser propulsion, first introduced by Kantrowitz[1], involves using a remote high-powered laser to supply power to a rocket vehicle. The laser power is used to heat an inert propellant, which is exhausted to produce thrust. Most approaches to laser thermal propulsion (as opposed to laser-electric propulsion, using photovoltaic cells to power an electric thruster) have relied on a laser-produced plasma to absorb the laser energy and couple it to the propellant; several reviews of these approaches exist in the literature [2,3]. The 1986 SDIO/DARPA workshop on Laser Propulsion[4] focused on developing laser propulsion for ground-to-orbit launch, and introduced an emphasis on developing very small, cheap, lightweight vehicles to minimize the size and capital cost of a laser launch system.

Laser-sustained plasma thrusters using continuous (CW) lasers appeared incompatible with this approach, and the subsequent SDIO Program concentrated on pulsed ablation thrusters[5]. These, however, required very large pulse energies and tightly-controlled pulse shapes and laser properties, and proved difficult to develop and test with available lasers.

In 1991, we proposed an alternative approach to high thrust-to-weight laser propulsion[6] using a high performance heat exchanger. This heat-exchanger (HX) rocket concept is reviewed briefly below. The HX rocket offers an overall performance comparable to that of pulsed solid-propellant laser rockets, launching an estimated 1 - 2 kg of payload to low Earth orbit for each megawatt of laser power[7]. Its inherently high efficiency compensates for the mass of the heat exchanger and propellant tank. The HX rocket also retains, in principle, the ability of the planar solid-propellant thruster to be steered from the ground, by using a multi-section heat exchanger and multiple nozzles; precise control of the laser beam would allow control of the thrust vector. The major advantages of the HX thruster are that it is omnivorous — it will work with almost any laser wavelength or pulse format, or even with incoherent sources for testing — and that it is comparatively easy to develop and test.

As of this time, we have planned the first phases of a development program for the heat exchanger thruster, and constructed a laboratory test facility for small (3 kW, 10 cm^2) heat exchangers. In this paper, we review the planned test program, and discuss the possibility of near-term tests of small free-flying laser-driven vehicles.

The Heat Exchanger Thruster

The heat exchanger (HX) rocket, sketched in figure 1, uses inert liquid propellant — normally liquid hydrogen for maximum specific impulse. The propellant is pressure-fed at very low pressure (by chemical rocket standards) into a flat, planar heat exchanger. The heat exchanger absorbs energy from a laser beam or (for test purposes) any other radiant energy source, and transfers that energy in the form of heat to the propellant, which is exhausted through a more-or-less conventional nozzle.

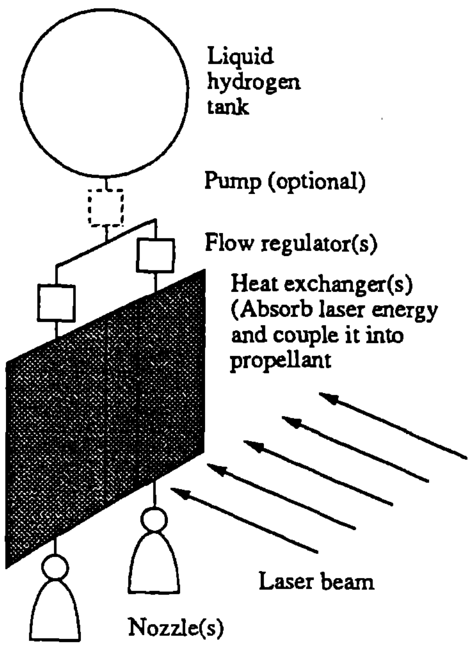

Fig. 1: Heat exchanger rocket concept

This is in principle very similar to solar-thermal thrusters, in which the radiant energy source is focussed sunlight.[8] However, the HX thruster differs from the solar-thermal thruster in several respects. The HX thruster, since it is intended for ground to orbit launch, requires extremely high power-to-mass ratios, for both the heat exchanger and the structure as a whole. Since

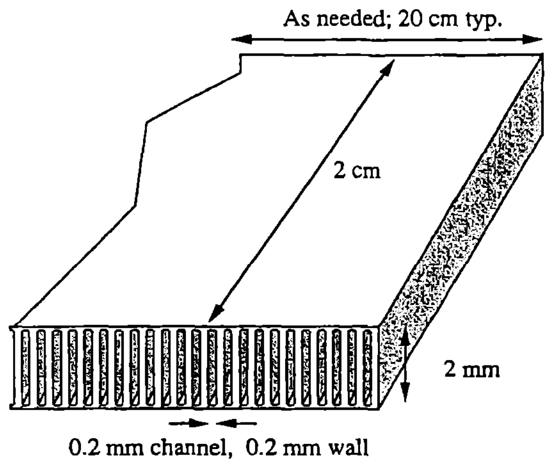

Fig. 2: Microchannel Structure

it is used with a high-flux laser source, and flies within the atmosphere, it neither requires nor allows a large concentrating optic. For economic use in a system which launches many small payloads, the heat exchanger and vehicle must be simple and inexpensive. Finally, as discussed in Kare[7], satisfactory performance requires only 600 - 800 s I_{sp}; achieving the maximum possible I_{sp} is secondary to keeping the heat exchanger cost and mass small. These I_{sp} values can be achieved with hydrogen at temperatures of 1000 to 2000 C; the lower end of this range, in particular, allows fabricating heat exchangers from relatively common materials such as nickel.

Heat Exchanger Design

The diverse requirements of the HX rocket are met by the heat exchanger design shown in figures 2 - 4. The basic heat exchanger structure (figure 2) is a "laminar flow microchannel" structure, initially developed at LLNL by Tuckerman[9] for liquid cooling of semiconductors; it is similar in principle to the heat exchanger developed several decades ago for the extremely high power density "DUMBO" nuclear rocket engine[10]. The microchannel structure provides very large surface area for heat transfer, while maintaining laminar flow to minimize pressure drop. The channel width is set by flow and heat transfer constraints on the working fluid (hydrogen); the channel height is set by the thermal conductivity of the heat exchanger material (in this case, nickel).

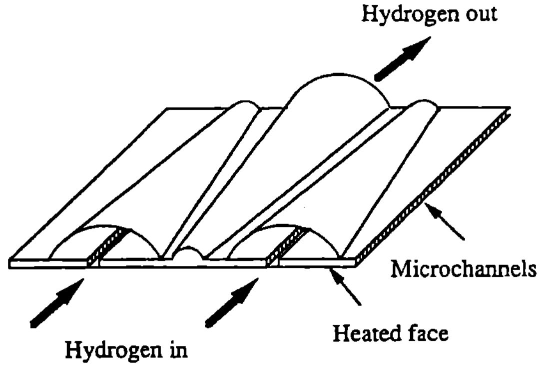

Fig. 3: Heat Exchanger Panel Assembly

The channel flow resistance and flow velocity are kept small by using short (2-3 cm) channels. Microchannel assemblies are grouped into panels as shown in figure 3, with headers on the back surface to carry propellant in and out. The maximum temperature rise in each panel is limited by flow stability considerations to approximately 4:1; it is also desirable from a materials standpoint to separate the heat exchanger into low- and high-temperature portions — for example, using copper (for its high thermal conductivity) for the lower-temperature sections and nickel or even tungsten alloys for high temperature sections. The panels are assembled into complete multistage heat exchangers as shown in figure 4. The overall configuration can be rectilinear or radial, as desired.

Heat exchangers of this type can be fabricated by a plating process: vertical fins are stacked together with spacers, and electroplated to form top and bottom layers; the plating material need not be the same as the fin material[11]. The spacer material can be etched out to form clear

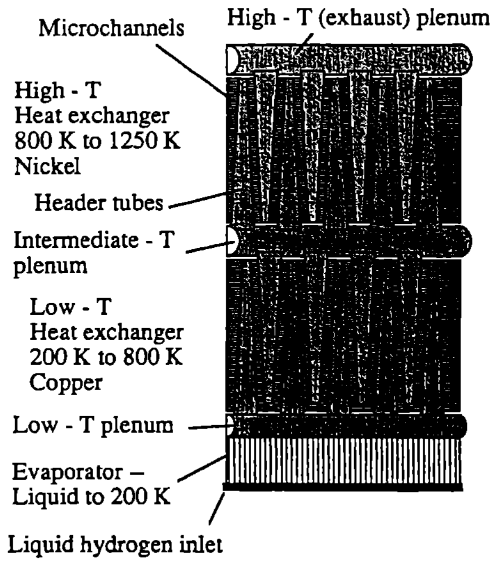

Fig. 4: Multistage Heat Exchanger

channels. By using appropriate blocks of spacer material, the headers can be formed together with the rest of the heat exchanger. A small number of test heat exchangers have been fabricated from nickel, using aluminum spacers, but incidental machining problems have prevented their completion.

Test program

The planned test and development program for the HX thruster consists of three phases, summarized in Table 1.

Low power tests:

Low power tests of a few seconds duration will be sufficient to confirm the basic operation and performance of heat exchanger segments. They will be conducted on single

Table 1: Outline of HX test program

Power level	Power, kW	Source	Working fluid	Tests
Low	3 - 10	Incandesecnt	He	HX properties
Inter-mediate	25 - 50	Arc, diode	He	Multistage HX
		CO_2 laser	H	Thruster demo
		CO_2 laser	N	"Bottle rocket"
High	1 MW (nom.)	? laser	He	Static test stand
		? laser	H	Sounding rocket

microchannel assemblies, typically 3 cm x 3 cm in size. At typical flux levels of 200 - 500 W/cm^2, these heat exchanger assemblies require 2 to 5 kW of input power. For safety reasons, these tests will be conducted with helium, rather than with hydrogen. Although the properties of He are significantly different from those of H_2, scaling of the results is relatively straightforward under the conditions encountered in the HX tests. In particular, despite the low pressures involved, dissociation of hydrogen will be a small effect up to the maximum temperatures used with nickel heat exchangers.

We have constructed an incandescent tungsten foil source for heat exchanger tests. This source uses two 0.012 cm (0.5 mil) strips of tungsten foil, mounted as shown in figure 5; these will operate in series at typically 40 V and 150 A to provide 6000 W total radiated power from 18 cm^2 (3 x 3 cm x 2 sides). The incandescent source is intended for intermittent full-power operation for a few seconds at a time, and thermal conductivity along the foils is low enough that no cooling of supports is required

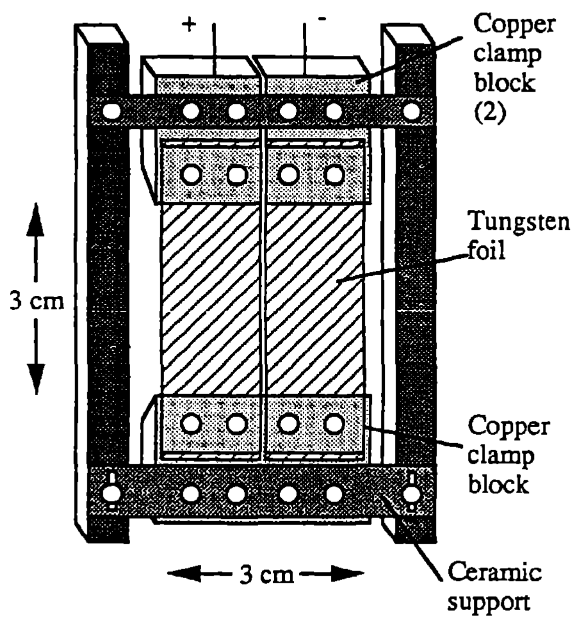

Fig. 5: "Light bulb" 300 W/cm^2 source

The foil source is mounted in a vacuum chamber (6" stainless steel vacuum "cross"); for initial tests the chamber was pumped down using a standard mechanical pump, backfilled with argon, and repumped, to an operating pressure of ≈10 mTorr. The incandescent source has been tested at power levels of over 150 W/cm^2 for several on-off cycles and tens of seconds of operation; although we have gone through several sets of tungsten foil, we expect to be able to run at at least 200 W/cm^2 routinely. Several alternative sources were considered, but were at least comparably expensive or difficult to set up and operate (e.g, arc lamps, lasers) for tests of this scale. Direct resistance heating of a surface coating, which has been used for testing microchannel semiconductor coolers, would require considerable development to achieve uniform heating over a wide temperature range and to survive large thermal expansion effects.

The heat exchanger under test is mounted in close proximity to the tungsten foil, so essentially all of the power emitted from one side of the foil impinges on the heat exchanger. A "dummy load" is mounted opposite the heat exchanger; this is a copper block with a surface coating similar in absorption properties to the heat exchanger. The temperature rise in the dummy load (or in its cooling water, since it can be water cooled for longer runs) provides a simple calorimetric measure of the power absorbed by the heat exchanger, and minimizes the heating of the rest of the chamber..

The overall test setup is shown in figure 6. Data are collected by a Macintosh computer running Labview; main data for testing will be the foil current and voltage, input and output gas pressure and temperature, and thermocouple temperatures at a variety of points on the back surface of the heat exchanger and on the dummy load. A Sierra Instruments mass-flow controller sets the gas flow rate over a 0-300 standard liter-per-minute range. Input pressure is nominally 500 kPa (70 psi) and is adjustable up to a limit of 1 MPa (150 psi) set by pressure safety requirements. The internal pressure in the heat exchanger can be varied at a given flow rate by an exit valve.

In addition to measuring the basic heat exchanger performance (primarily thermal and flow resistances), this small testbed will allow testing the maximum operating temperature of the heat exchangers. Since the nickel heat exchangers, in particular, will operate close to the softening point of nickel, we expect to test several small heat exchangers to destruction to establish the safe operating limits for the materials and fabrication techniques used. Actual flight heat exchangers would have an operating life of less than 10 minutes, so the yield points of materials can be approached more closely than they would be in longer-lived components. These tests will also provide the steep thermal gradients associated with actual operation, and will therefor test the resistance of the plated microchannel assemblies to differential expansion and related failures.

Unfortunately, due to a combination of machining difficulties and resource limitations, no high temperature heat exchanger tests have been completed as of this writing, so we are unable to report any test results at this time.

Intermediate power tests

Assuming the basic heat exchanger construction and performance are verified, three types of tests are planned at intermediate power levels of 25 - 50 kW. Initially, a simple static test of two- and three-stage heat exchangers, using helium, will be done to verify the performance of such multistage devices, including headers and plenums, and to test the reliability of interstage joints between differing materials. The required radiant flux and fluence can be obtained from a variety of sources, including large area arc lamps[12] and solar furnaces. LLNL has a program to produce high-powered laser diode arrays in quantity for pumping solid-state lasers; such arrays can also provide very intense incoherent illumination. The actual heat exchangers would be ≈6 x 10 cm, and would be fed cold helium gas.

A demonstration of actual static thruster operation using hydrogen can be done using either laser or solar-concentrator sources. We are aware of at least two possible sites, both equipped to handle the necessary gram-per-second quantities of hydrogen; one an existing solar-thermal propulsion test site at the Phillips Laboratory in Edwards, CA[13] and the other the Laser Effects Test Facility[14] at the Phillips Laboratory in Albuquerque, NM. Other possible sites certainly exist. The goal of this test would be sustained (30

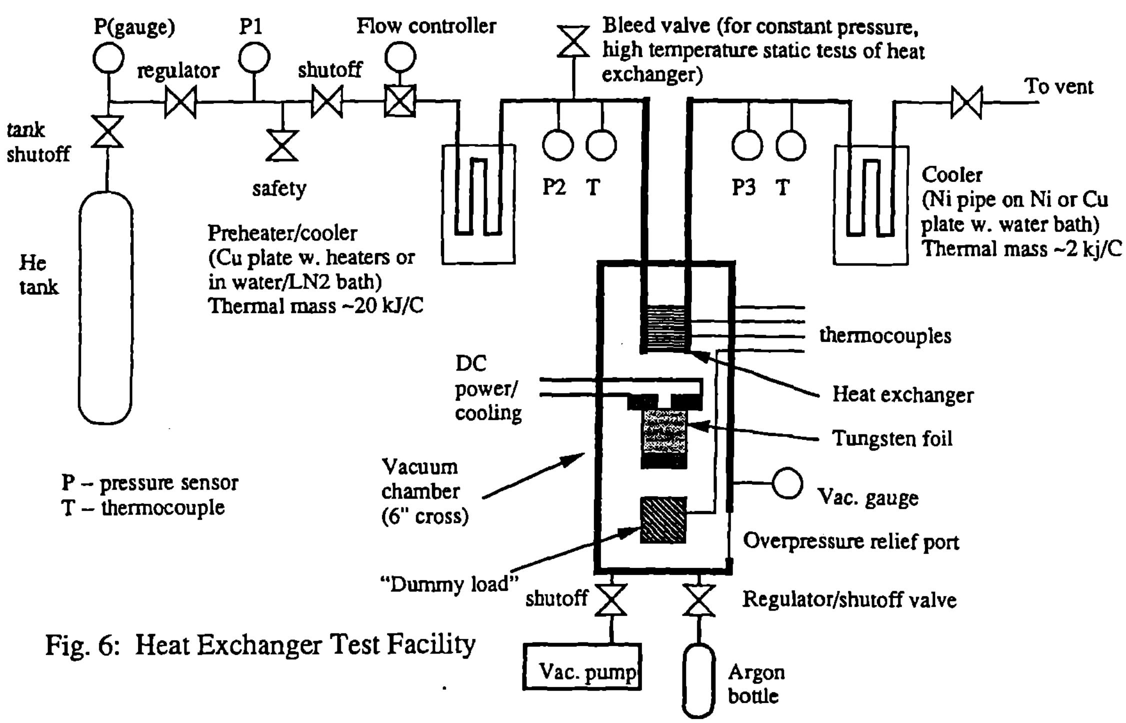

Fig. 6: Heat Exchanger Test Facility

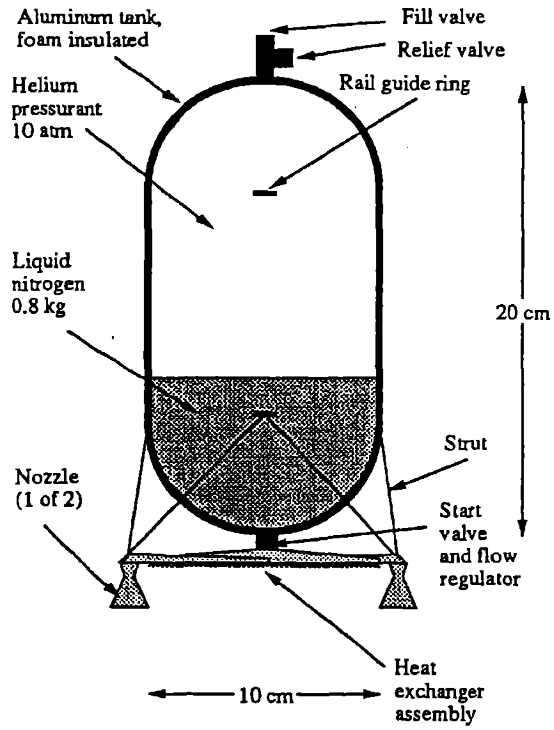

Fig. 7: Heat exchanger bottle rocket

second) operation of a 25 to 50 kW thruster with approximately 600 s I_{sp} and near-unity efficiency. The thrust produced would be 10 - 20 N.

Finally, figures 7 and 8 show design sketches for a "bottle rocket." This is a self-contained vehicle which uses liquid nitrogen, pressurized with helium, as a propellant. The 14-fold higher molecular mass of N_2 over H_2 means that the I_{sp} of the bottle rocket will be at most 600 s x $(1/14)^{1/2}$, or about 140 s. However, the thrust is increased by the same ratio, so that even with a 40 kW source, a total thrust of ≈30 N will be produced. The bottle rocket has a nominal dry mass of less than a kilogram, so even with 0.6 kg (30 seconds worth) of propellant on board it will be capable of lifting itself easily against gravity.

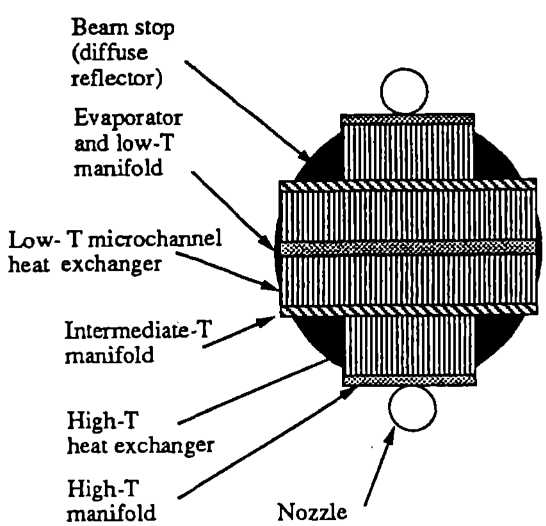

Fig. 8: Heat exchanger configuration

The bottle rocket is intended to be flown on a high power laser beam, although it can (and will) be tested with any of the static sources discussed above. Of particular concern will be the smooth, uniform feeding and vaporization of the initially-liquid propellant. The Phillips Laboratory laser effects facility can provide a suitable beam; other lasers in this power range do exist. Although the bottle rocket is intended only for captive flight (e.g., along a vertical wire or rail) it will have a split heat exchanger and two nozzles, allowing single-axis control tests.

High power tests

Beyond the 50 kW power level, the HX thruster encounters the problem common to all laser-driven thrusters: the lack of high-average-power lasers. Even incoherent radiant sources are rare, although some very large solar concentrators exist. However, the HX thruster is adaptable to almost any type of laser, including CO_2, chemical, and both RF and induction free electron lasers. It is also sufficiently simple to allow tests to be done at almost any site, anywhere in the world.

As an example of what could be done, we consider a "sounding rocket" test vehicle scaled to a hypothetical 1 MW laser with a beam divergence of 10 μradians (i.e., a spot diameter of 1 meter at 100 km). For a diffraction-limited laser beam, this would require a 2.6 meter mirror at 10.6 microns, or a fractional-meter mirror at shorter wavelengths. The sounding rocket is 40 cm in diameter, and has a dry mass of 3 kg, nominally 1 kg heat exchanger, 1 kg hydrogen tank, and 1 kg structure and telemetry. It is launched at rest at some initial altitude (by an aircraft, balloon, or chemical rocket booster stage) and flies vertically until either it

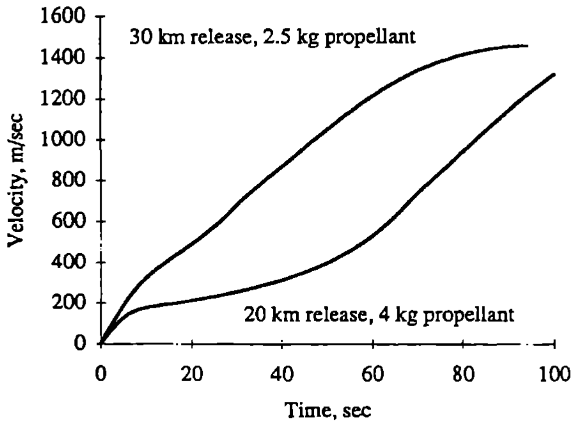

Figure 9: Sounding rocket velocity

exhausts its propellant or the laser flux drops to a negligable value; after that, it coasts upward. Using a simple spreadsheet model, we assume that at low altitudes the rocket absorbs 80% of the beam energy; at higher altitudes the collected energy falls as the square of the altitude ($1/r^2$). The model includes drag due to a simple exponential atmosphere with a scale height of 8 km, and a vehicle drag coefficient of 0.2.

Two cases are shown in figures 9 and 10. In one, the rocket is released at 20 km with 4 kg of hydrogen on board. From figure 9, it is clear that the rocket's speed is limited by drag for most of its flight. In this case, it runs out of propellant at a moderate altitude. On the other hand, if the rocket is released at 30 km, with only 2.5 kg of hydrogen, it is relatively unaffected by drag, but soon runs out of laser beam, so that its thrust and acceleration fall

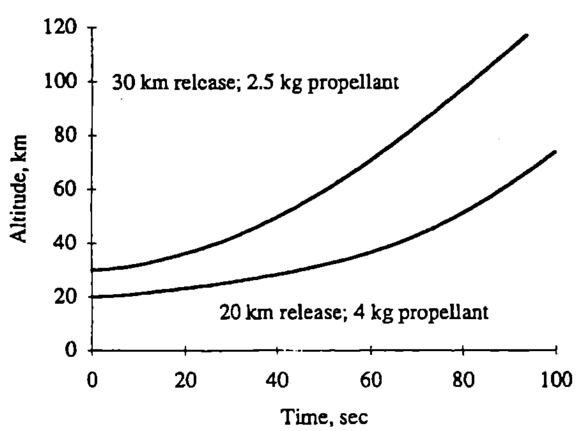

Figure 10: Sounding rocket altitude

off. In both cases, the rocket reaches well over 1 km/s and will continue to coast upward for another ≈100 km.

Although the parameters of this sounding rocket can be varied widely, these examples show the general characteristics: the sounding rocket mass will mass a few kg and be a few 10's of cm across, and it will need to carry only a few kg (a few 10's of liters) of liquid hydrogen. It will require a high-altitude launch to keep drag within reason, but would be able to reach velocities in excess of 1 km/sec and altitudes of hundreds of km.

A sounding rocket launch would obviously be a substantial step beyond any static testing or short-range flights. It would require fully solving the problems of vehicle stability and control (not to mention laser pointing and tracking, and a host of other factors). However, a successful test on this scale — with an effective laser range at least a few times the atmospheric scale height — would demonstrate essentially all the capability needed to fly to orbit. The next step would be flight to orbit, and would require only an increase in laser power and beam quality, both by factors of less than ten.

Conclusion

Heat exchangers have been designed which are capable of converting laser or other radiant energy into heat in a hydrogen propellant, at a flux level approaching 1 kW/cm^2 and a power density approaching 1 kW/g. Tests of small (few-kW) heat exchangers using helium gas can be done at any time. Tests of larger multi-stage heat exchangers, complete hydrogen-fuelled thrusters, and small flying vehicles can be done using available facilities. Testing of much larger heat exchangers and sounding-rocket-class free-flying vehicles depends primarily on the availability of large lasers, but almost any type of laser can be used. Such sounding-rocket tests would lead directly to a laser launch system when and if multi-megawatt average power lasers (and associated optics) become available.

Acknowledgement

Work at Lawrence Livermore National Laboratory is conducted under the auspices of the U.S. Department of Energy, under contract number W-7405-ENG-48

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